A General Method for Designing the Transformer of Flyback Converters Based on Nonlinear FEA of Electromagnetic Field Coupled with External Circuit

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***Abstract*-This paper presents a general method for designing the transformer of flyback switching AC-DC converters based on nonlinear finite element analysis (FEA) of electromagnetic field coupled with external circuit. For that, the variation patterns of the PWM duty ratio and the current flowing through the windings of transformer versus the input voltage are introduced first, and then several important principles for the design of the transformer are given by using analytical method. As the magnetic saturation and control delay possess heavy influence on the safety of the operation, a MATLAB/Simulink based simulation model, in which both the nonlinear differential inductance and the control delay are included, is built to predict the converter transient performance. The nonlinear differential inductance is calculated by a general program of nonlinear 2-D FEA in Matlab/Simulink surrounding. By running the model, the performances of the converter with different loads and input voltages are obtained. Simulation results are in good agreement with theoretical analysis.**

I. INTRODUCTION

Flyback converters are often selected for small power applications. As to the special structure of over current protection mode in flyback converters, two important factors should be carefully considered: the nonlinearity of the differential inductance of transformer and the design of the third winding which is often used to supply the PWM controller.

For the differential inductance, many power electronic engineers often decide it at the rated operational state by some analytical programs [1], and the obtained inductance is often an apparent inductance instead of a differential inductance. As the magnetic saturation is difficult to be considered by this method, it causes some uncertain factors in performance analysis. Although the method based on nonlinear finite element analysis (FEA) of electromagnetic field coupled with the external circuit has high accuracy, at a high operational frequency of over 50 KHz, the field-circuit direct coupling method will consume excessive computation time [2]. For static transformers, as the positions of all the finite elements are fixed and the eddy current loss can be omitted due to the low conductivity of transformer core, the field-circuit indirect coupling method can have the same accuracy but higher efficiency, and it is adopted in this paper.

For the third winding of transformer, according to [3], as the design of the over current protection circuit is based on the primary winding of transformer and the control delay caused by the RC-filter circuit and transfer delay of integrated circuit (IC) such as UC3842, the current flowing through the third winding will increase when the input voltage or the output load increases. This will increase the power loss of the output diode, D2, as shown in Fig. 1. For that, a method for designing the third winding based on the selection of a suitable transition point from the operation mode of over current protection (OCP) to that of under voltage protection (UVP) is presented.

In this paper, the transformer design is divided into two steps. The major parameters of the transformer are decided by the accustomed analytical method first and then are verified by a field-circuit indirect coupling method based simulation model. By running the model in MATLAB/Simulink surrounding, the performances of the converter with different loads are obtained.

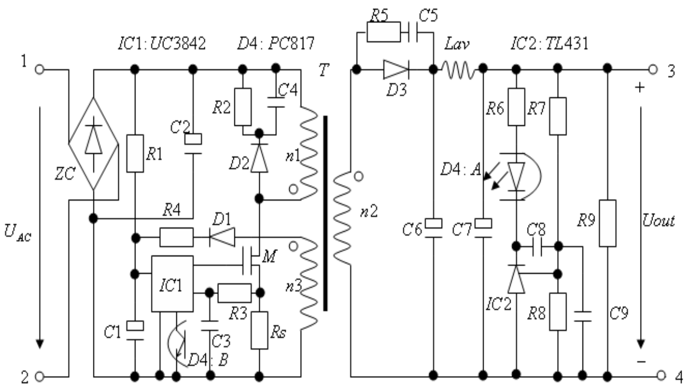


Fig. 1. Typical circuit of flyback AC to DC converter

II. TYPICAL CIRCUIT OF FLYBACK AC TO DC CONVERTER

The typical circuit of the flyback switching AC to DC converter is shown in Fig. 1, where both a transformer with three windings and a PWM controller of UC3842, as shown in Fig. 2, are included.

The voltage of VCC for starting UC3842 is V_{START} = 16 V. There are three methods which can cause the PWM output of UC3842 to be closed: (1) After starting up, if $V_{c1} \leq 10$ V, the PWM output of UC3842 will be closed; (2) The voltage of the ISENSE is above 1 V; and (3) COMP (1) is circuit-shorted to the ground by PC817. Three operational modes correspond to the three states when the PWM output is closed: voltage control mode (VCM), over current protection mode (OCP), and under voltage control mode (UVC). According to the energy conservation, UC3842 in the ON state can be modeled by a small resistance of R_{ICON}, and in the OFF state by a very large resistance, R_{ICOFF}, e.g. 2 MΩ. Both the typical rise time and fall time of the output section of UC3842, according to the manual, are 50 ns, and cannot exceed 150 ns. In order to maximize the system safety when operating in OCP or UVP mode, the rise time, T_{RISE}, is chosen as 50 ns, and the fall time, T_{FALL}, is chosen as 150 ns. The time delay time, T_{DELAY}, to output port is about 150 ns.

In order to describe the proposed method easily, a flyback switching AC-DC converter with input voltages of 85-264 VAC/50Hz, rated output of 15 VDC/1.2 A, and switching frequency of 100 kHz is used as the example in this paper.

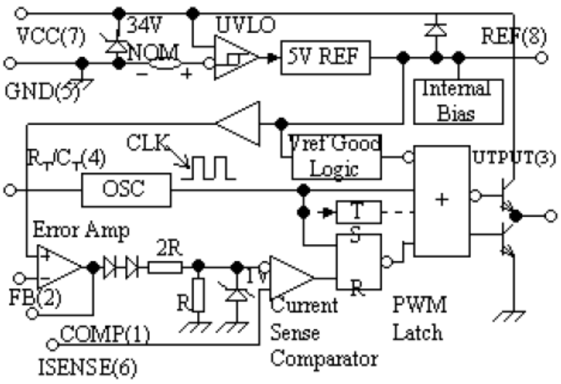


Fig. 2. Functional block diagram of UC3842

III. ANALYTICAL METHOD FOR DESIGN OF THE TRANSFORMER

In this section, the variation patterns of the PWM duty ratio and the current flowing through the windings of transformer versus the input voltage are introduced firstly, and then the analytical method for the design of the transformer is presented. Before the analysis, the following simplifications are made: 1) Passive components (resistance, inductance and capacitance) are considered as linear, time invariant and frequency independent. 2) Switching components (diode and power MOSFET): the power MOSFET in the ON state is modeled by a zero resistance and in the OFF state by an infinite resistance, e.g. $R_{INF}=10^{20}$ Ω. The output capacitance and the inductance of the leading wires are considered as zero. The diode in the ON state is modeled by a constant voltage battery V_F plus a constant forward resistance R_F, and in the OFF state by an infinite resistance, e.g. $R_{INF}=10^{20}$ Ω. During the charge-carrier's lifetime, the diode junction capacitance and leading wire inductance are zero. 3) All the control delays and the other factors such as RCD or RC filter and parasitical parameters of electronic parts are ignored.

A. Operation Characteristic of Flyback Converter

According to [3], when the converter operates in continuous conducting model (CCM), the PWM duty ratio, D, is decided by

$$D=\frac{n_1(V_{out}+V_F)}{n_1(V_{out}+V_F)+n_2V_{in}} \tag{1}$$

where n_1 and n_2 are the numbers of turns of the primary winding and the secondary winding, V_{out} is the output voltage of converter, V_{in} the voltage across the capacitance ($C2$) shown in Fig. 1, and V_F the voltage of the equivalent battery of output diode, $D1$. According to (1), two conclusions can be drawn: that the duty ratio of PWM depends on the equivalent input and output voltages only and it is not affected by the load, and that when the input voltage increases the PWM duty ratio will decrease.

Suppose that the transformer has an efficiency of 100% (from the view of engineering as the efficiency of most transformers is above 98%), and keeps with the same rated output voltage, the maximal output power of the converter with any input voltage of V_V is decided by

$$P_{vm}=V_vD_v(I_{p1\max}-\Delta I_{p1v}) \tag{2}$$

where

$$\begin{cases}\Delta I_{p1v}=\dfrac{V_v}{2L_1}D_vT\\ D_v=\dfrac{n_1(V_{out}+V_F)}{n_1(V_{out}+V_F)+n_2V_v}\end{cases}, \tag{3}$$

L_1 is the differential inductance of the primary winding of transformer and I_{p1max} is its maximal current. From (2) and (3), it can be found that the maximal output power will increase when the input voltage increases.

Keeping with the rated output voltage and current, the maximal current, I_{p1H}, the minimal current, I_{p1L}, and the average current, I_{p1AV}, flowing through the primary winding of the transformer can be decided by

$$\begin{cases}I_{p1AV}=\dfrac{(V_{out}+V_F)I_{out}}{V_vD_v}\\ I_{p1H}=I_{p1AV}+\Delta I_{p1v}\\ I_{p1L}=I_{p1AV}-\Delta I_{p1v}\end{cases} \tag{4}$$

According to the above equation, it can be found that all the maximal current, the minimal current and the average current will decrease when the input voltage increases. Furthermore, considering (3), it can also be found that under the same input voltage, all of them will increase if the output voltage decreases. Combining these two conclusions, it can be drawn that in the range of input voltage and output voltage, all the maximal current, the minimal current and the average current reach the maximum if the converter operates under the maximal input voltage and the minimal output voltage. Under this condition the power consumed by the output diode, $D1$, is also maximal.

From the above conclusions obtained from (1)-(4), the variation patterns of the PWM duty ratio and the current flowing through the windings of transformer with different input voltage, output voltage and out current are illustrated in Fig. 3.

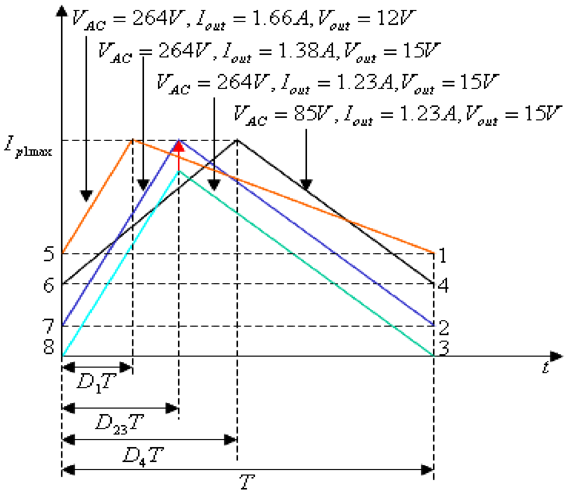


Fig. 3. Operational characteristics of flyback converter

B. *Analytical Method for Designing the Transformer*

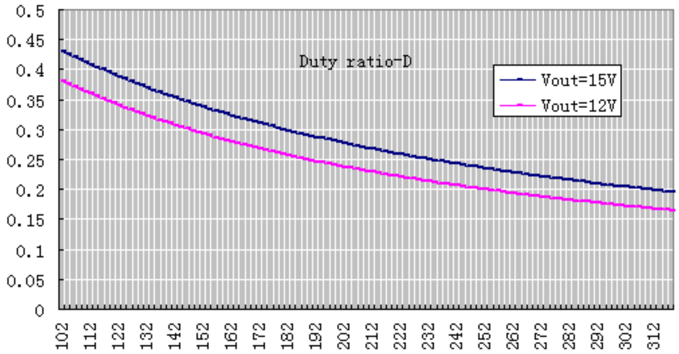
It has been concluded that the maximal PWM duty ratio happens when the converter with the rated load operates under the minimal input voltage. For the above example, the conditions are: U_{ac}=85 V, V_{out}=15 V, and I_{out}=1.23 A. In general, the maximal PWM duty ratio is below 50%. With the same rated load, the minimal PWM duty ratio happens when the converter operates under the maximal input voltage. For the above example, the condition is: U_{ac}=264 V. According to Fig. 3, the DC excitation under the maximal PWM duty ratio is bigger than that under the minimal PWM duty ratio. In order to increase the efficiency of the magnetic material utilization, it is preferred that under the maximal input voltage, the converter with the rated load should operate in the critical conduction mode.

Furthermore, it has been concluded that in the range of input voltage and output voltage, all the maximal current, minimal current and the average current reach the maximum when the converter operates under the maximal input voltage and the minimal output voltage, and under this condition the power consumed by the output diode is also maximal. Along with that the voltage of UC3842 under the operation mode of UVP is 10 V, it is preferred to increase the output voltage so that the power consumed by the output diode, D1, is reduced, and the voltage of UC3842 should be selected slightly higher than 10 V.

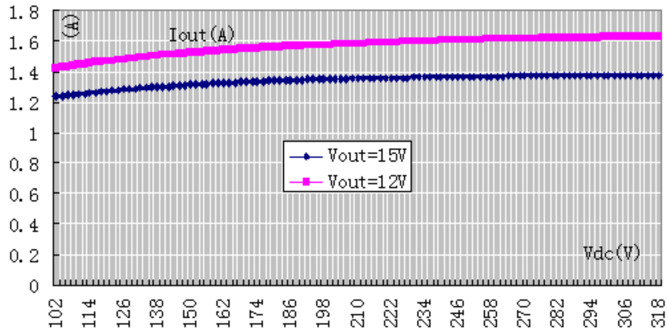
Based on the above principles, the program to design the transformer can be obtained. The major parameters of the transformer are obtained and shown in Table I. Fig. 4 shows the performance analyses by using (1)-(4), from which it can be found that they are in good agreement with the theoretical analysis.

TABLE I. MAJOR PARAMETERS OF TRANSFORMER IN A FLYBACK CONVERTER

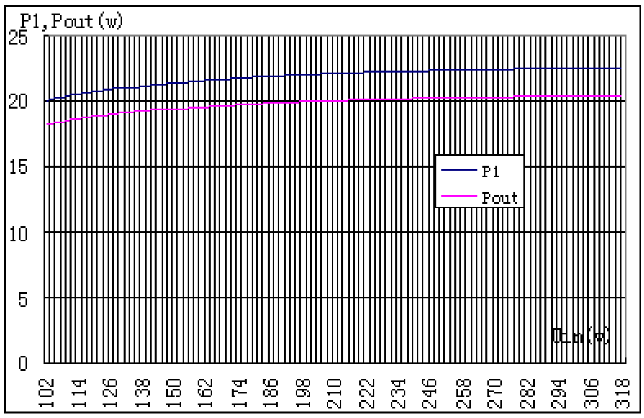
1	Magnetic Core type	EE-25
2	Magnetic material type	TDK PC40
3	Bobbin Type	EE-25 (8 pin)
4	Inductance of the primary winding, *L*	0.865 mH
5	Numbers of turns of windings, *n1*:*n2*:*n3*	58:12:9
6	Frequency of PWM, *f*	100 KHz
7	Length of air gap, l_g	0.168 mm
8	Maximal magnetic flux density, B_{max}	298.0 mT
9	Maximal PWM duty ratio, D_{max}	0.428



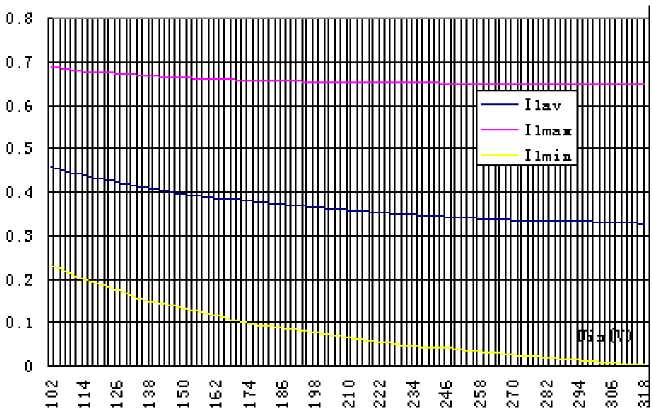
(a: upper line for *Vout*=15V, lower line for 12V)



(b: upper line for Vout=12V, lower line for 15V)



(c: upper line for *P1*, lower line for *Pout*)



(d: top line for I_{1av}, middle line for I_{1max} and bottom line for I_{1min})

Fig. 4. Performance analysis (all against input voltage): (a) PWM duty ratio, (b) output current, (c) input power and output power with an output voltage of 15 V, and (d) I_{1max}, I_{1av} and I_{1min} of the converter with the rated load.

IV. VERIFICATION USING NUMERICAL MODEL

For verifying the results obtained from the analytical method, a field-circuit indirect coupling model is employed.

By adding the AC-DC rectifying circuit to the flyback switching DC-DC model introduced in [2] in which all the parasitical parameters, control delay and the differential inductance are considered, the complete simulation model of flyback AC-DC converter can be obtained and shown in Fig. 5.

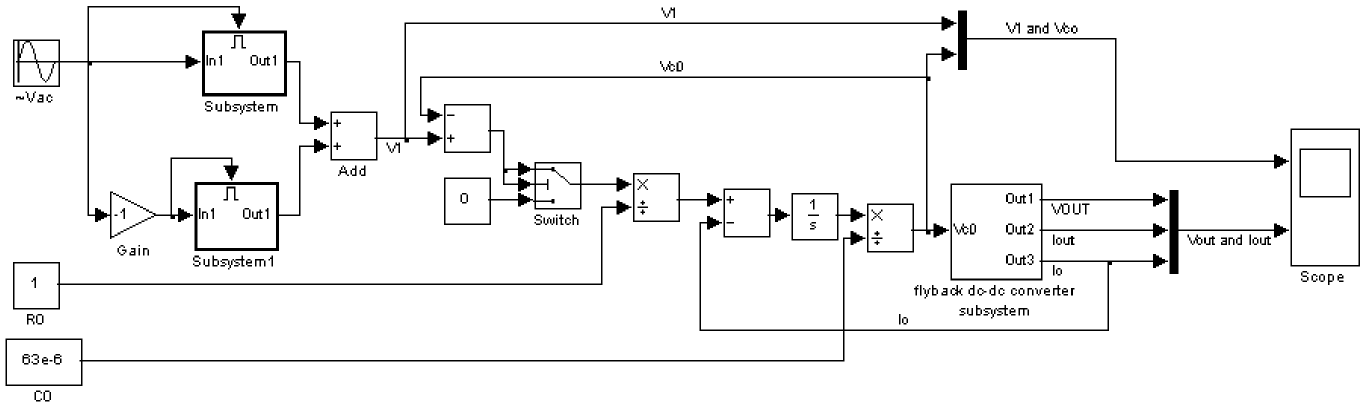


Fig. 5. Complete simulation model of an AC-DC flyback switching converter

The equivalent circuit of transformer is shown in Fig. 6. As the magnetic saturation and the differential inductance are difficult to be considered by the analytical method, a 2-D nonlinear finite element method is applied to obtain the differential inductance, which includes two steps: (1) For a given winding current, i, conduct a non-linear field analysis to find the flux linkage of windings, ψ_m; (2) When the flux densities in two consecutive time steps are obtained, the differential inductances can be calculated by

$$L_m(i) = \frac{d\psi_m(k)}{di} = An_1\frac{B_m(k)-B_m(k-1)}{i(k)-i(k-1)} \tag{5}$$

where A is the cross-sectional area of transformer core, n_1 the number of turns of the primary winding, and subscripts (k) and (k-1) refer to the kth and (k-1)th steps, respectively.

Fig. 7 plots the 2D magnetic force lines of an E25-transformer with air gap. In order to obtain the differential inductance of 0.865 mH with respect to an excitation current of 0.765 A flowing through the primary winding as that shown in Table I, the length of air gap is changed to 0.15 mm.

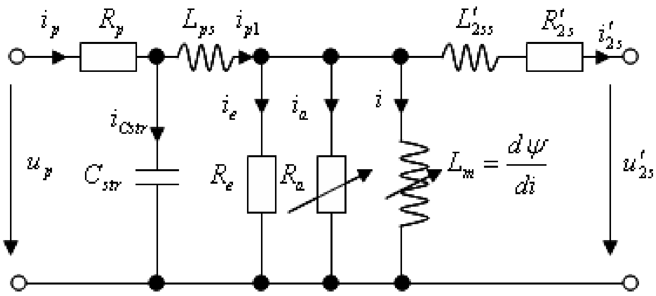


Fig. 6. Equivalent circuit of the transformer

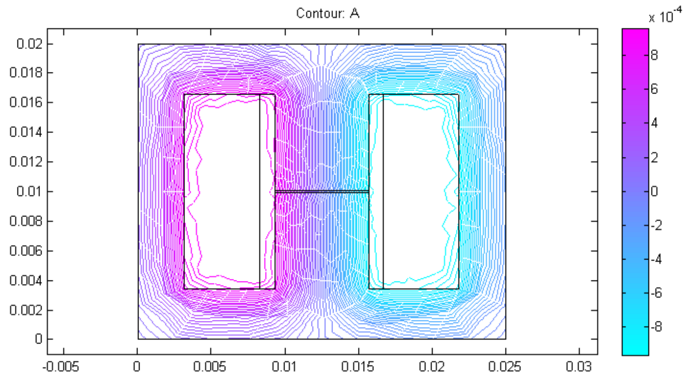
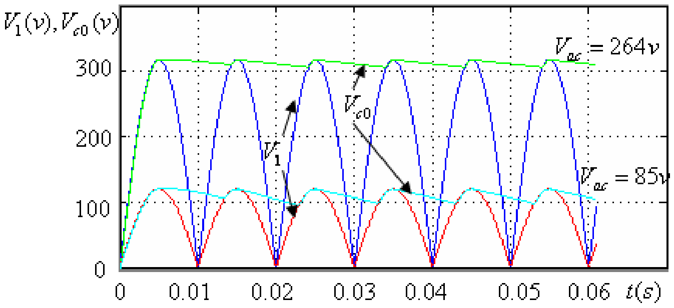


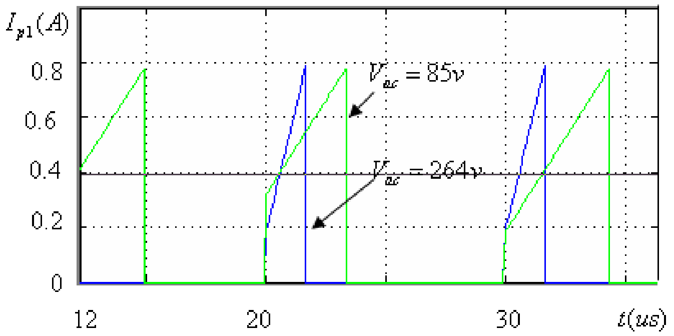
Fig. 7. Magnetic force lines of E25-transformer

Other key parameters of the converter include: $R1$=160 KΩ/1W, $C1$=10 μF/25V, $C2$=63 μF/35V, R_S=1.3 Ω, $R3$=1.2 KΩ, $C3$=100 pF, MOSFET: SSS6N60A, $R3$=0 Ω, D1: MUR1620, D2: UF4006, D3: 1N4148, $R2$=100 KΩ/1W, $C2$=3.3 nF/1000V, and C_o=1000 μF/25V. By inputting these parameters into the model and running the model in MATLAB/Simulink surrounding, several analysis results are obtained and shown in Fig. 8, all of them are similar to those shown in Fig. 4.

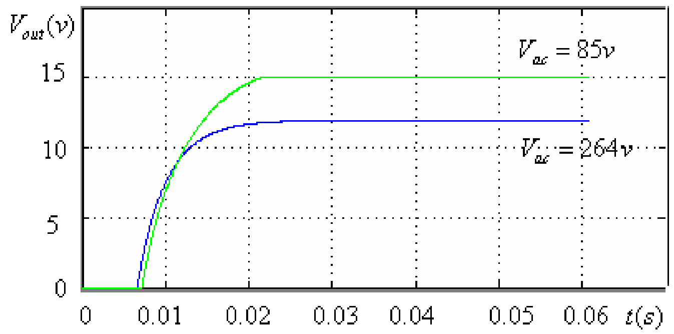
Under the input voltages of 264V and 85V, respectively, Fig. 8(a) shows the output voltage of the rectifying circuit and the voltage across the input filter capacitor, C2. Fig. 8(b) plots the current waveforms flowing through the primary winding of converter with the rated load. Fig. 8(c) illustrates the output voltage of 15V under the input voltage of 85V, and the output voltage of 12V under the input voltage of 264 V, respectively. Finally, Fig. 8(d) shows the output currents of the converter with output voltages of 15V/12V.



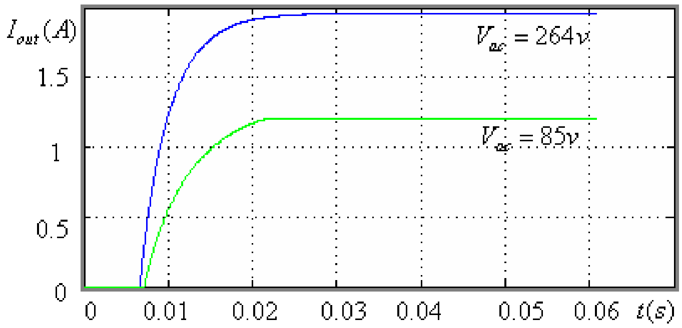
(a)



(b)



(c)



(d)

Fig. 8. Simulation results (under different input voltages V_{ac}=85 V and 264 V): (a) Output voltage of rectifier v_1 and voltage across the capacitance V_{c0}; (b) Current flowing through the MOSFET of the converter with the rated load; (c) Output voltage V_{out}; and (d) Output current under the output voltage 12/15V.

V. Conclusion

This paper presents a general method for designing the transformer of flyback switching AC-DC converters, which is divided into two steps: firstly an improved analytical method is employed to obtain the basic parameters of the transformer, and then the detailed performance of a flyback converter is predicted by using a field-circuit indirect coupling method based simulation model. Simulation results show good agreement with theoretic analysis.

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